PERFORMANCE CRITERIA FOR 12-INCH CONCRETE SUBSTANTIAL DIVIDING WALLS

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ABSTRACT

Large numbers of 12-inch concrete substantial dividing walls (SDW's) exist throughout the munitions production, operations, maintenance, and storage infrastructure. These walls are often used to subdivide explosives for quantity-distance definition and to provide operational shields for personnel. Current Army and Air Force safety regulations assume that 12-inch SDW's will prevent propagation for up to 425 pounds of Class/Division 1.1 explosives and will function as an operational shield for up to 15 pounds of Class/Division 1.1 explosives.

Data developed in the last 30 years do not support the simple application of these explosive limits. An effort is currently underway to more accurately define the capacity and performance of 12-inch SDW's for a wide range of applications. In this report, the development of 12-inch SDW's explosive limits will be outlined. Analytical models used in the ongoing study will be detailed. Finally, preliminary results will be discussed.

1.0 Introduction

Existing Department of Defense (DOD) and related military service explosive safety standards allow the use of "dividing walls" as an acceptable means to subdivide explosive quantities and, thereby, reduce the maximum credible explosive event used for siting and operations. Dividing walls have been constructed in U.S. military and commercial explosive manufacturing, handling, and storage facilities for more than 50 years. Criteria for the use of dividing walls in the DOD are provided in the explosive safety standards of each of the services. These standards are governed by the DOD Ammunition and Explosives Safety Standard, DOD 6055.9-STD.

One widely used structural element used to subdivide explosives is a 12-inch reinforced concrete wall. Reinforcement provided in this wall is normally #4 bars (one-half inch diameter bars) spaced at 12 inches on center, with horizontal and vertical bars on each face of the wall. The typical configuration of this wall is provided in figure 1.

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2.0 Substantial Dividing Wall Definition

In DOD 6055.9-STD, a dividing wall is defined as a "wall designed to prevent, control, or delay propagation of an explosion between quantities of explosives on opposite sides of the wall." In this definition, to "prevent" propagation implies Category 3 protection while to "delay" propagation implies Category 4 protection. In chapter 9 of the standard, "Structures to Resist the Effect of Accidental Explosions" (TM 5-1300, AFM 88-22, and NAVFAC P-397) is referenced for the design of intervening barriers or dividing walls. No further guidance is provided in DOD 6055.9-STD regarding the use and design of dividing walls.

Within the Army, at government owned facilities, the guidance provided in DOD 6055.9-STD is implemented through the AMC Safety Manual (AMC-R 385-100). In AMC-R 385-100, a substantial dividing wall is defined as "an interior wall designed to prevent detonation of quantities of explosives on opposite sides of the wall." Section 5-6a of the safety manual further states that "substantial dividing walls will be designed in accordance with TM 5-1300, Structures to Resist the Effects of Accidental Explosions, to prevent propagation of detonation by blast and by ammunition or wall fragments." Both of the foregoing statements are in agreement with the guidance provided in DOD 6055.9-STD. In addition, both statements imply that substantial dividing walls should be designed to provide Category 3 protection.

Unlike DOD 6055.9-STD, however, AMC-R 385-100 provides specific instructions regarding the use of existing "12 inch reinforced concrete walls." In section 5-6b of the manual, it is stated that "Reinforced concrete wall (RCW) not less than 12 inches thick, are effective in preventing propagation between bays when the donor quantity does not exceed 425 pounds of class 1, division 1 explosives . . ." Later in the section, a bay siting limit of 425 pounds of explosive is prescribed for existing facilities. It is implied that the 425 pound limit will provide only Category 4 protection.

For ammunition and explosives production by DOD contractors, safety criteria are provided in the "DOD Contractors' Safety Manual for Ammunition and Explosives," DOD 4145.26-M. In DOD 4145.26-M, a "substantial dividing wall" is defined as "An interior wall design to prevent simultaneous detonation of explosives on opposite sides of the wall. However, such walls may not prevent propagation." The manual, thereby, asserts that substantial dividing walls will provide only Category 4 protection.

DOD 4145.26-M allows the use of SDW's for bay limits of up to 425 pounds of explosives. In addition, the manual provides detailed criteria for the construction of SDW's.

FIGURE 1 - TYPICAL 12" REINFORCED CONCRETE DIVIDING WALL

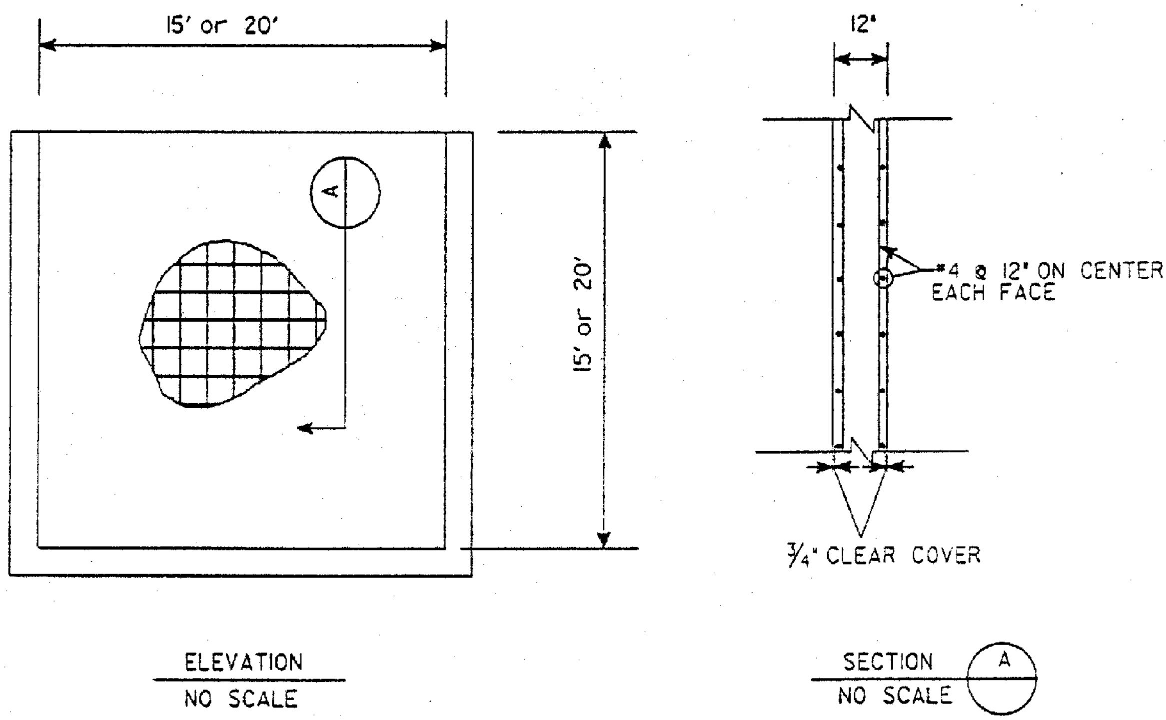

Figure 1- Typical 12" Reinforced Concrete Dividing Wall

> Reinforced concrete walls may vary in thickness, but will be at least 12 inches thick. At a minimum, both faces will be reinforced with rods (deformed steel reinforcing) at least 1/2 inch in diameter. The rods will be spaced at not more 0than 12 inches on center horizontally and vertically, interlocking with the footing rods and secured to prevent overturning. Rods on one face will be staggered with regards to rods on the opposite face and should be approximately 2 inches from each face. Concrete should have a minimum of 2500 psi compressive strength.[2]

Unlike AMC-R 385-100, DoD 4145.26-M does not explicitly state that the 425 pound bay limit must be applied only to "existing" construction. DOD 4145.26-M can instead be interpreted to allow the construction of new 12 inch reinforced concrete walls to prevent the simultaneous detonation of up to 425 pounds of explosives.

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[2]Department of Defense, DoD Contractors' Safety Manual for Ammunition and Explosives (Washington, D.C., 11 April 1988), p. xiv.

In conclusion, current DOD standards generally recognize existing 12-inch reinforced concrete walls as being capable of preventing the simultaneous detonation of up to 425 pounds of explosive. The construction of most existing 12-inch concrete SDW's follows the criteria provided in DOD 4145.26-M, as discussed earlier in this section.

3.0 Historical Development of DOD SDW Criteria

Since World War II, 12-inch concrete SDW's have been extensively used to prevent the simultaneous or sympathetic detonation of explosives on the opposite side of the wall. The historical development of the current explosive limit of 425 pounds TNT for these walls is provided in this section of the report.

When 12-inch concrete SDW's were first used by the military, there was great uncertainty as to the maximum weight of explosives which could be safely separated by them. According to June 1944 correspondence between various groups of the Safety and Security Division, Office Chief of Ordnance, "There is one problem which arises with embarrassing frequency however, for which we have literally no data whatsoever and which we have solved up to the present time entirely by guesswork; namely, that of interior substantial dividing walls."[3]

The June and October 1942 supplements to the Ordnance Safety Manual allowed a maximum explosive weight of 20,000 pounds for 12-inch concrete SDW's. In June 1945, the maximum weight was reduced to 15,000 pounds. At the same time, however, the Field Director of Ammunition Plants advised that a maximum of 65,000 pounds was permissible.

Due to the resulting uncertainty, a SDW test program was conducted by the Department of the Army under the direction of the Army-Navy Explosives Safety Board. Tests were performed in 1944 and 1945 and used SDW's of varying thickness and configuration. All tests were carried out at the Naval Proving Ground in Arco, Idaho. Donor and acceptor charges varied; they included bulk explosives, bombs, and torpedoes in general use at the time.

Six of the tests were performed on 12-inch concrete SDW's. The charge weights used in these tests ranged from 6,384 pounds amatol to 30,000 pounds TNT. A minimum stand-off distance of 3.0 feet was used in all the tests. It is interesting to note that a sympathetic detonation was reported in all six tests. In four of the tests, a high order detonation was reported. The remaining two tests reported low order detonation(s). As a result of the Arco tests, the ASESB recommended, in 1950, that no more than 5,000 pounds of explosives be separated by 12-inch concrete SDW's to prevent their simultaneous detonation.

During the 1950's, there was continuing discussion and concern over the validity of the 5,000 pound explosive limit. According to the conclusions of a 1959 presentation to the ASESB, "The present Board standard of a 5000-pound limit for simultaneous detonation as now

[3]Correspondence from Safety and Security Division, Office Chief of Ordnance, quoted by Ralph Ilsley in <u>The Effectiveness of Reinforced Concrete Dividing Walls for Protection against Simultaneous Detonation, Explosion, and Communication</u>, 19 January 1959, p.3

expressed, is not based on a reasonable risk . . . The lack of conclusive data in the region of 200 to 3,000 pounds indicates that tests to simulate important types of dividing wall usage would be advisable."[4]

As a result of this presentation, a "Work Group to Determine the Effectiveness of Dividing Walls in the Prevention of Propagation of Explosives" was formed by the ASESB to investigate the capacity and design of dividing walls. Under the direction of the work group, tests were conducted on SDW's of varying type and thickness. Many of the tests were conducted on 12-inch concrete SDW's. According to a 1964 summary report:

> The test results point out the inadequacies of the present standard one foot concrete dividing wall for the quantities of explosives being stored today. The safe limit for this wall for prevention of propagation is in the vicinity of 150 to 250 lbs. depending on type of weapon or explosive and storage condition.[5]

In addition, the summary report states that the incidence of propagation is dependent on many variables, not just on the wall thickness and the charge weight. According to the report," . . . It was found that the incidence of propagation varied with wall thickness, donor charge weight, proportions of the cubicle, location of donor charge, type of acceptor, and casing and orientation of acceptor." The report concludes that ". . . It was evident that a critical range exists [for a given acceptor charge] where incidence of propagation is a function of velocity and mass of striking wall fragments."[6]

Based on the foregoing discussion, it is unclear how the current 425 pound limit was selected. A possible explanation, however, can be found in the minutes of various ASESB meetings. According to these minutes, it appears that the 425 pound limit was initially based on the approval of siting for one particular weapon. The weapon in question had a maximum explosive weight of 425 pounds TNT and a heavy casing. Later discussions suggest that the 425 pound limit should only be applied to heavy cased weapons. Another, lower maximum quantity was recommended for thin cased weapons. Unfortunately, it appears that no further action was taken. As a result, the 425 pound limit became a "de facto" standard for 12-inch concrete SDW's.

4.0 Sensitivity of Explosives to Fragment Impact

As discussed in section 3.0, the incidence of propagation for a given acceptor charge is primarily dependent on the velocity and mass of the wall fragments which strike it.

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[4]Ibid., p. 14.

[5]Arthur Schwartz, Report on Summary and Analysis of Full Scale Dividing Wall Tests and Comparison with Analytically Predicted Results (Dover, N.J., Ammunition Engineering Directorate, Picatinny Arsenal, March 1964), p. 3.

[6]Ibid., p.7.

Numerous tests have been conducted to evaluate the sensitivity of various types of explosives. The results of these tests are summarized in this section of the report.

From 1963 to 1967, an extensive test program was carried out by the Naval Weapons Center to investigate the sensitivity of explosives to multiple fragment impact and to peak overpressure. The study was performed under the direction of the ASESB. Multiple fragment impact tests were conducted by throwing standardized packets of sand, gravel, or concrete rubble against explosive target acceptors. Impact velocities of the packets were chosen to approximate the velocity of dividing wall fragments following an explosion within storage or manufacturing cubicles. Target acceptors included bare explosive charges, simulated and actual warheads, and solid propellant motors.

A total of 162 tests were conducted using 13 different acceptors. The report summarizes the results of the fragment-impact tests as follows:

> The fragment-impact test data indicated that there was a wide range of impact velocities at which a given acceptor may detonate. For example, in the tests with the standard dividing wall acceptor, the lowest impact velocity in which a detonation occurred was 400 ft/sec, and the highest impact velocity at which no detonation occurred was 550 ft/sec . . . Hence, a fairly large region of uncertainty is evident from this overlap.[7]

The report concludes that variability in sensitivity for various explosive acceptors should be expected. The report recommends that data be acquired for each acceptor of interest. Through so doing, it was hoped that ultimately, acceptors could be divided into classifications based on their relative sensitivity.

5.0 Hydrocode Analysis of Substantial Dividing Walls

In February 1994, a study was initiated by the U.S. Army Corps of Engineers, Huntsville Division, to evaluate 12-inch concrete SDW's. The purpose of the study is to more accurately define the capacity and performance of these walls. As a part of the study, hydrocode analyses will be performed on typical dividing walls subjected to blast loadings from bare explosive charges. The analyses will provide estimates of the velocity of wall fragments following a detonation in a typical explosive manufacturing bay. Various charge weights will be considered; it is anticipated that charge weights will range from 15 to 425 pounds TNT.

Two wall conditions will be investigated. Analyses will be performed on walls with supports on two sides (side and bottom edges) and on walls with supports on three sides (side, bottom, and top edges). The cubicle to be evaluated has inside dimensions of 14 feet wide by 14 feet deep by 14 feet high. Charges are located at a stand-off distance of 3 feet from the side wall. The cubicle configuration and charge location to be used in the study are depicted in figure 2.

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[7]URS Systems Corporation, Investigation of Explosives Sensitivity to Fragments and Overpressure (Part 1) (China Lake, CA, Naval Weapons Center, March 1969), p. 39.

Analyses performed to date have been used to validate the proposed finite element model by comparing analytical results to actual test results. A detailed discussion of the finite element model and the validation process follows.

5.1 Finite Element Model

During the past 25 years, the finite element method has been increasingly used as an analytical research tool. In structural analysis, the method first discretizes a structure into a set or sets of structural components, each set with a similar geometric pattern and material characteristics. Each pattern employs a specific type of finite element with a specific structural shape. Finite elements are interconnected with adjacent elements by nodal points. In this study, two basic finite element types will be used, one type modeling the steel reinforcement (i.e., a 1D truss element), and a second type modeling the concrete (i.e., a 3D brick element).

FIGURE 2 - TYPICAL MANUFACTURING AND STORAGE CUBICLE CONFIGURATION.

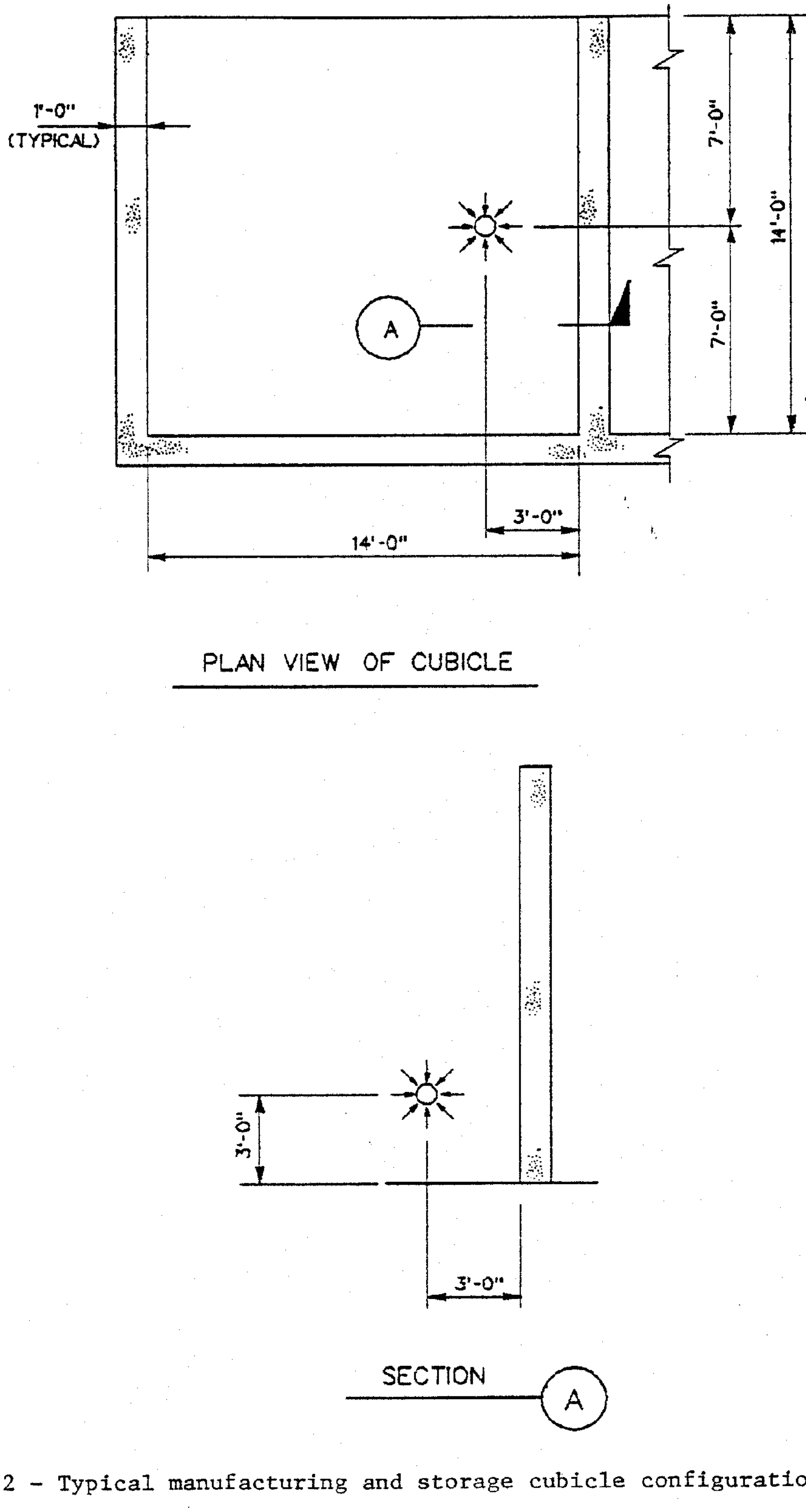

Figure 2 - Typical manufacturing and storage cubicle configuration.

One and two dimensional finite element models, while requiring less analytical effort than three dimensional models, often produce such variability in results that their use must be validated against a full 3-D model. In this study, the use of a 3-D model allows the representation of the actual geometry and boundary conditions of the wall. In addition, a 3D model permits the representation of two-way slab behavior.

The three-dimensional Lagrangian hydrocode, DYNA3D, developed by Lawrence Livermore National Laboratory, is widely recognized and commonly employed for the numerical modeling of reinforced concrete structures subjected to blast effects. A modified DYNA3D code was proposed for use in this study.

The concrete and steel material models in the modified DYNA3D code have been significantly revised to enhance their representation of material behavior under rapid, dynamic loading. The enhanced material models should provide accurate predictions of wall response and fragment velocities. Predictions of fragment masses are expected to be less reliable. Therefore, these predications will, if possible, be corroborated with test data. A detailed explanation of the revised material models follows.

5.1.1 Steel Reinforcement Model

Steel reinforcement is modeled discretely using 1-D truss elements. A strain-rate dependent elastic-plastic material model is adopted to include exponential fits in the post-yielding regime. The model also includes a tension cutoff to simulate bar rupture at failure strain. In explanation, a bar is allowed to fracture; it may still elongate but no further load will be carried by it. In this way, the deformed geometry is maintained and the structure remains continuous throughout the deformation process. Ultimate strains in the reinforcement are normally in the range of 10% to 15%.

5.1.2 Concrete Model

The concrete material model used by DYNA3D has been modified as follows:

Concrete Compressive Behavior: A full three-invariant plasticity model has been added to the existing concrete material model to capture the differences between triaxial compression and triaxial extension.

Concrete Tensile Behavior: Early time debris are created by the spalling of the back cover of the SDW. Accurate prediction of initial debris velocity and spalling requires accurate modeling of concrete behavior in tension, including cracking and post-cracking strain-softening behavior. The enhanced model has incorporated both tensile and compressive strain softening.

Rate Effects: Dynamic enhancement of the failure surfaces, which provides for the incorporation of the added strength of a material when loaded at high strain rates, follows the recommendations provided in TM 5-1300.

5.2 Validation Process

The proposed finite element model has been successfully employed by the Defense Nuclear Agency (DNA) in other studies. Unfortunately, the DNA studies have used wall thicknesses, reinforcement ratios, and charge locations different from those under consideration in this study. Therefore, to ensure the accuracy of analytical results, a validation process has been performed.

After an extensive literature search, two full-scale tests of 12-inch concrete SDW's were identified for use in the validation process. The tests were performed in the early 1960's and were part of a larger test program, the results of which were used to develop basic information for the design of dividing walls. Most of the tests performed under the program used charge weights far in excess of 425 pounds. The two tests chosen for the validation process represent the lower end of charge weights employed, 272 pounds and 496 pounds TNT respectively. In the analyses, it was assumed that the concrete yield strength was 3,000 psi and the steel yield strength was 40,000 psi. Data from the tests follows.

Test 1: In the literature, the test is referenced as the first of two C-6 tests. The test was performed in a three wall cubicle without a roof. Cubicle walls were 12" thick and used reinforcing of #4 bars @ 12", each way, each face. Inside plan dimensions of the cubicle were 11'-5" by 16'-0". The charge weight was 272 pounds. The charge was located approximately 2.5 feet from the side wall. Damage to the wall was listed as "complete destruction"; the maximum fragment velocity was reported as approximately 500 feet per second.

Test 2: In the literature, the test was referenced as test C-5. The test was also performed in a three wall cubicle without a roof. Cubicle walls were 12" thick and used reinforcing of #4 bars @ 12", each way, each face. Inside plan dimensions of the cubicle were 11'-5" by 16'-0". The charge weight was 496 pounds. The charge was located approximately 2.5 feet from the side wall. Damage to the wall was listed as "complete destruction". The maximum fragment velocity reported for this test is classified but was used to validate the finite element model.

The blast loading on the walls were calculated using the SHOCK computer program. Hydrocode analyses were continued to approximately 0.045 seconds after initial loading. Since the fragment velocity data for test C-5 are classified, no discussion of the analytical results for this test will be provided.

Analytical results for the side wall of test C-6 are depicted in figures 3 through 9. In figures 3 through 5, deformed meshes for the slab are shown at 0.010, 0.025, and 0.040 seconds after loading. Analysis of the slab's deformed shape at these times indicates that, due to the low charge stand-off distance, initial deformation of the wall occurs primarily near the charge, with the upper half of the wall showing little deformation. Even at 0.40 seconds, the upper edge of the wall has undergone relatively minor deformation.

FIGURE 3 - DEFORMED SLAB MESH APPROXIMATELY 0.010 SECOND AFTER LOADING.

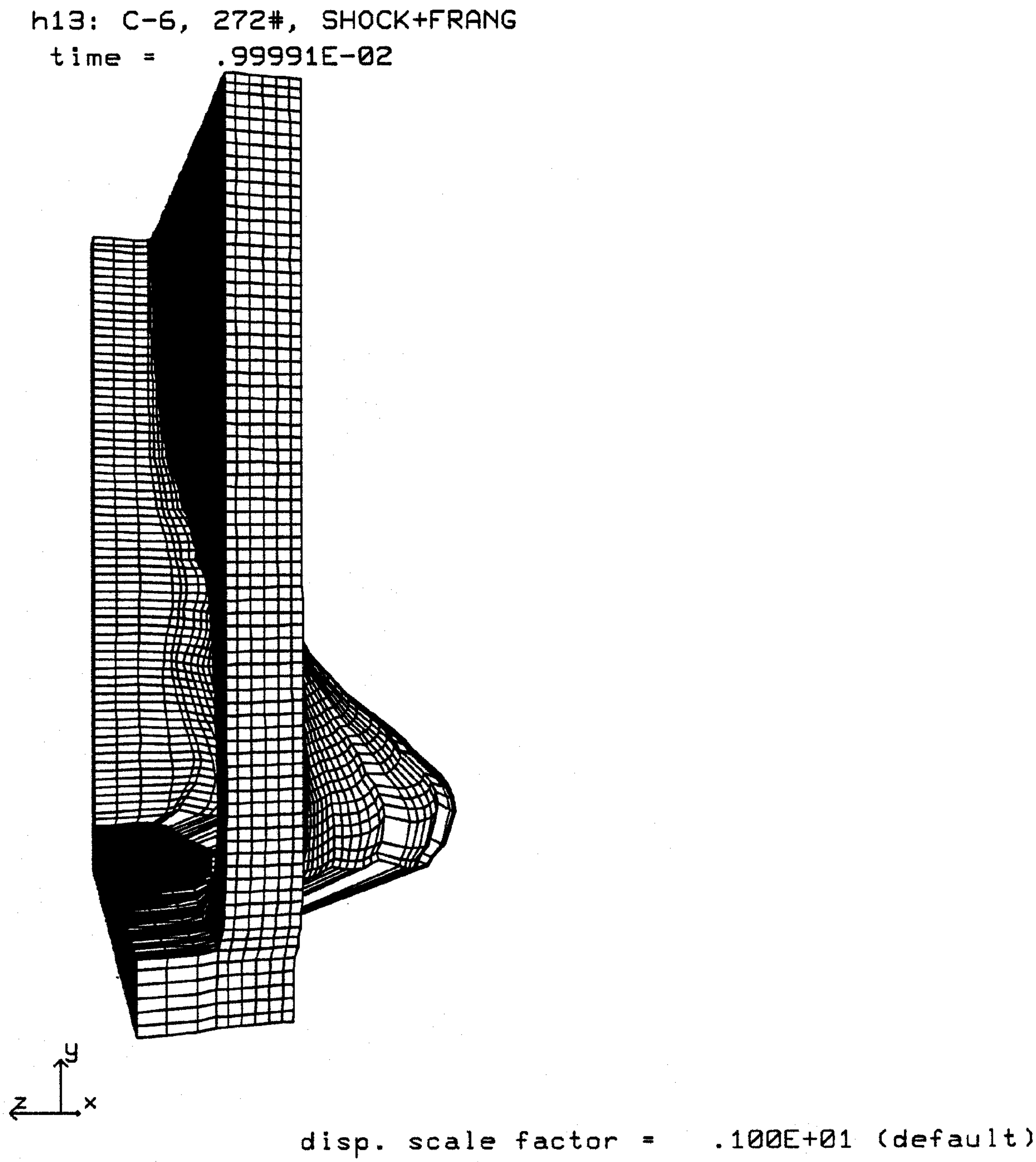

Figure 3 - Deformed slab mesh approximately 0.010 second after loading.

FIGURE 4 - DEFORMED SLAB MESH APPROXIMATELY 0.025 SECOND AFTER LOADING.

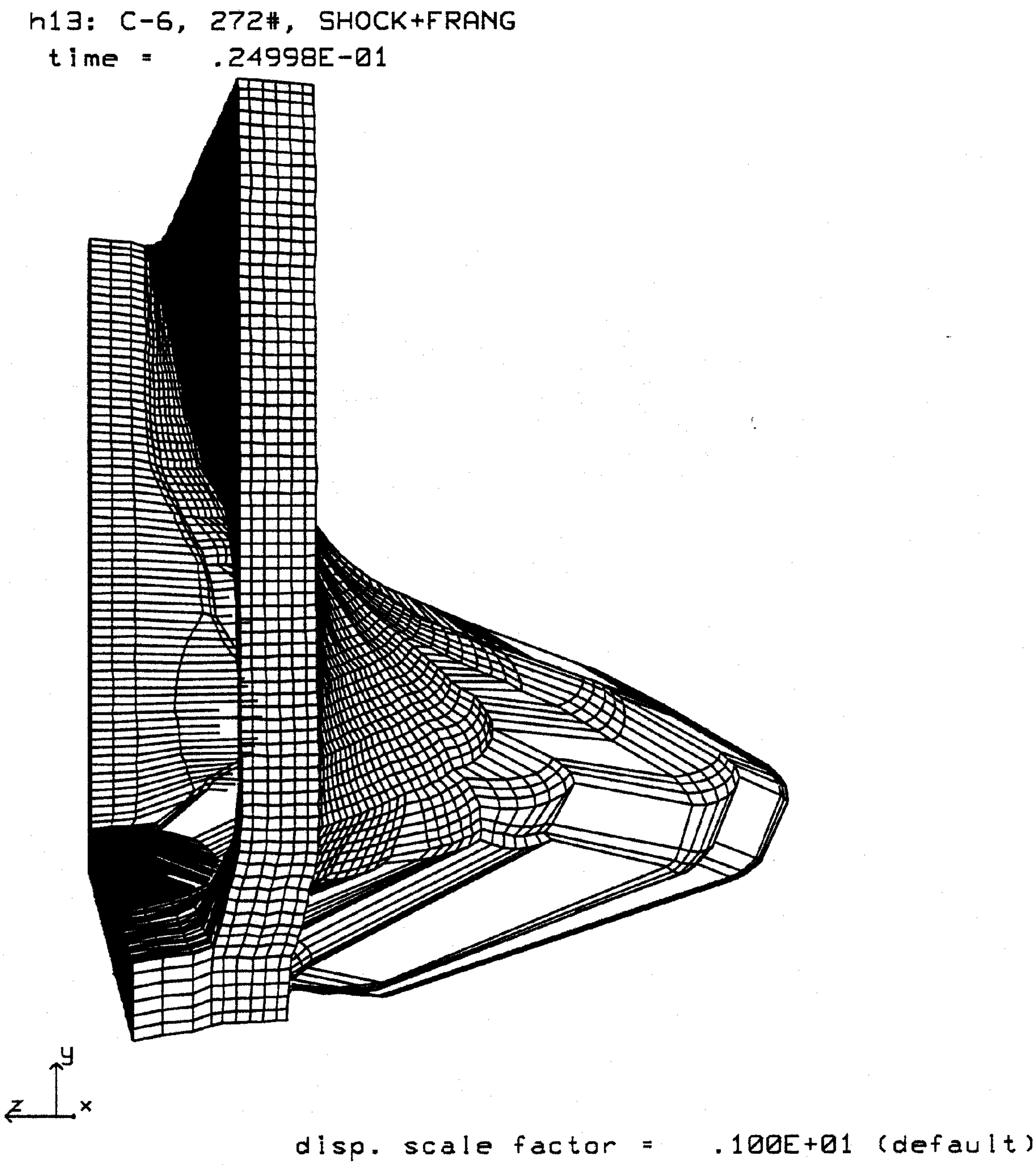

Figure 4 - Deformed slab mesh approximately 0.025 second after loading.

FIGURE 5 - DEFORMED SLAB MESH APPROXIMATELY 0.025 SECOND AFTER LOADING.

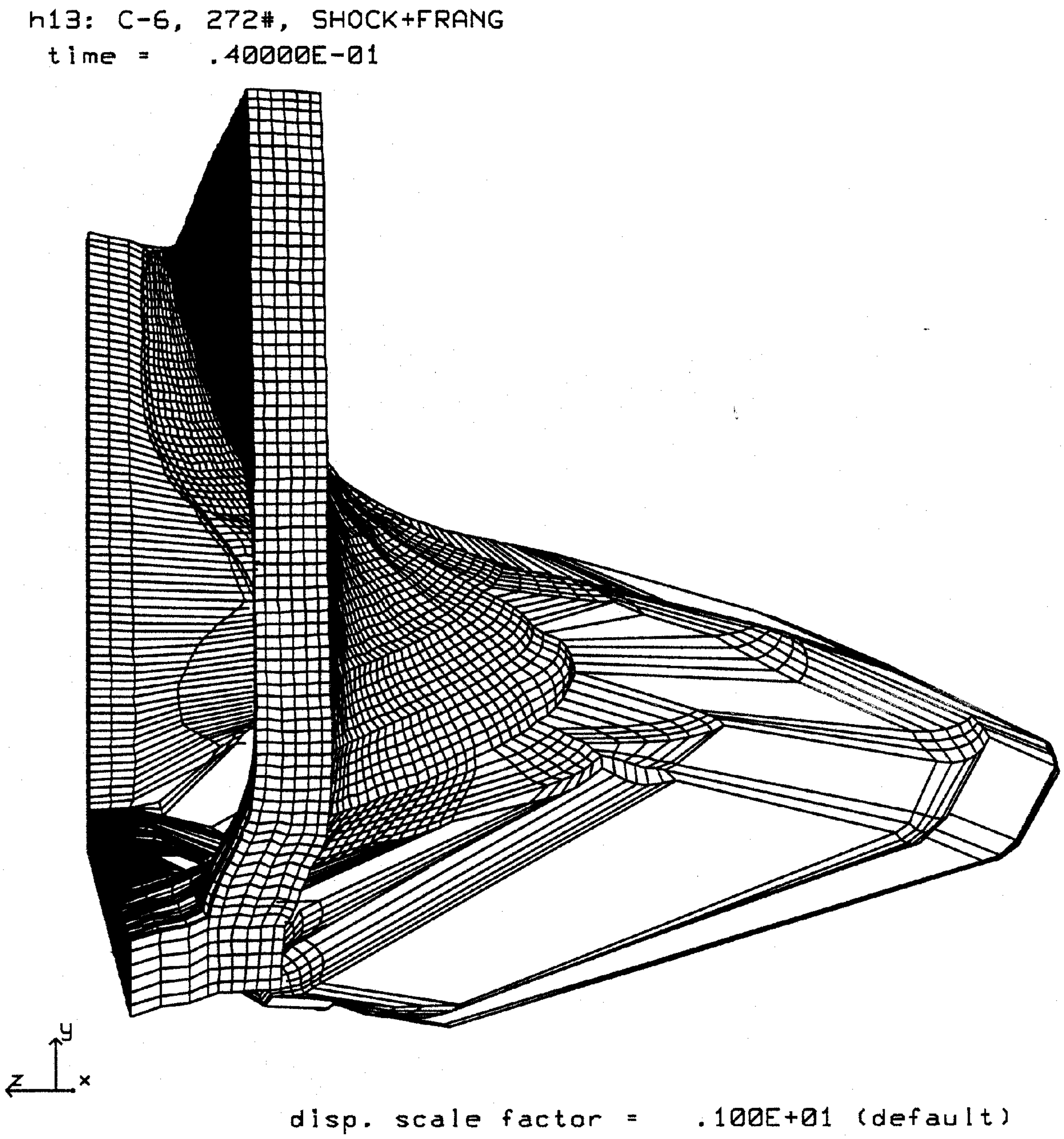

Figure 5 - Deformed slab mesh approximately 0.040 second after loading.

Figures 6 and 7 depict the deformation of steel reinforcing bars at 0.025 and 0.040 seconds after loading. As expected, the steel reinforcement directly in front of the charge fractures under the loading considered. A sample of strain histories in the reinforcing bars directly in front of the charge is provided in figure 8. As can be seen, both the inside and outside bars fracture at approximately 0.05 seconds after loading.

Maximum wall fragment velocities at four locations near the charge are provided in figure 9. It should be noted that the maximum predicted fragment velocity of approximately 470 feet per second agrees closely with the test measurement of approximately 500 feet per second. This finding supports the conclusion that the numerical model is adequate.

To summarize, the fragment velocities and extent of wall damage predicted by the finite element analysis agree closely with the actual test data, thereby providing verification of the proposed model. Unfortunately, no test data were available for 12" concrete SDW's subjected to blast loadings from lower charge weights, so further validation of the code was not possible..

6.0 Conclusions

During the 1960's, the Department of Defense established an explosive limit of 425 pounds for 12-inch concrete substantial dividing walls. The 425 pound limit was instituted to prevent the simultaneous detonation of explosives on both sides of the wall. Data developed during the last 30 years do not support the simple application of this explosive limit.

According to the available test data, the probability of explosive propagation through 12-inch concrete SDW's depends largely on two factors, the velocity and mass of the wall fragments produced by the detonation and the sensitivity of the receiver explosive. Explosive limits for the walls should reflect consideration of these factors.

Data exist on the sensitivity of certain munitions and explosives. In addition, as discussed in this paper, a finite element model has been developed whereby the velocity of wall fragments can be predicted. The model has been verified against available test data and will be used to estimate fragment velocities resulting from the detonation of charges of various weights. Through analysis of the predicted fragment velocities and the available sensitivity data, it is hoped that consistent, risk based explosive limits can be developed for 12-inch concrete SDW's.

7.0 Acknowledgements

We would like to extend our deep thanks to Dr. Chester Canada of the DDESB for his kind assistance in securing test reports and background information for use on this project. Funding for the project has been provided by the U.S. Army Technical Center for Explosives Safety (USATCES) under the Supporting Studies for Explosive Safety in Underground Magazines program. Program coordinators are Dr. Ken Williams of USATECS and Dr. Ben Carnes of the U.S. Army Corps of Engineers, Waterways Experiment Station.

FIGURE 6 - DEFORMATION OF STEEL REINFORCING BARS AT APPROXIMANTELY 0.025 SECOND AFTER LOADING.

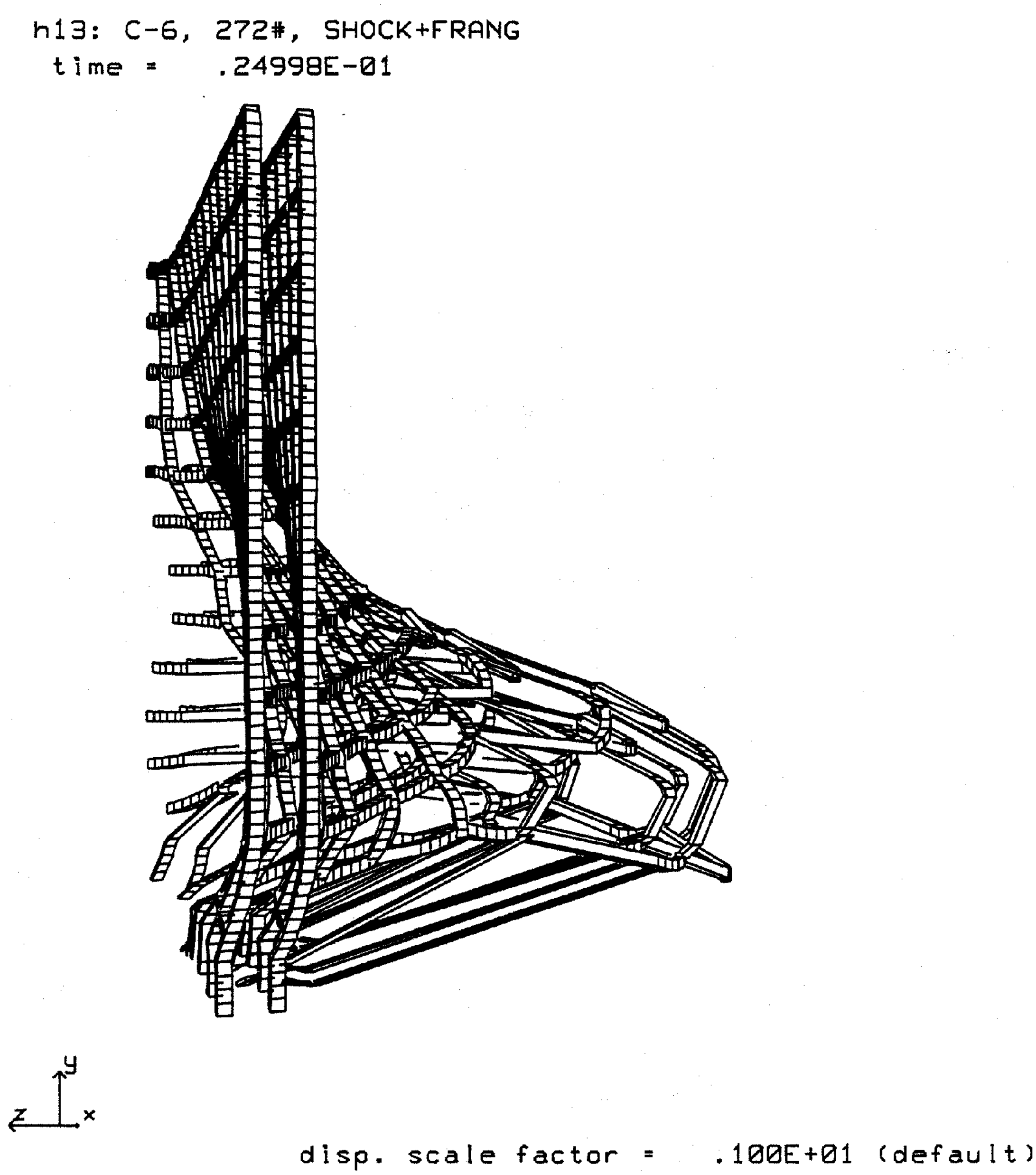

Figure 6 - Deformation of steel reinforcing bars at approximately 0.025 second after loading.

FIGURE 7 - DEFORMATION OF STEEL REINFORCING BARS AT APPROXIMANTELY 0.040 SECOND AFTER LOADING.

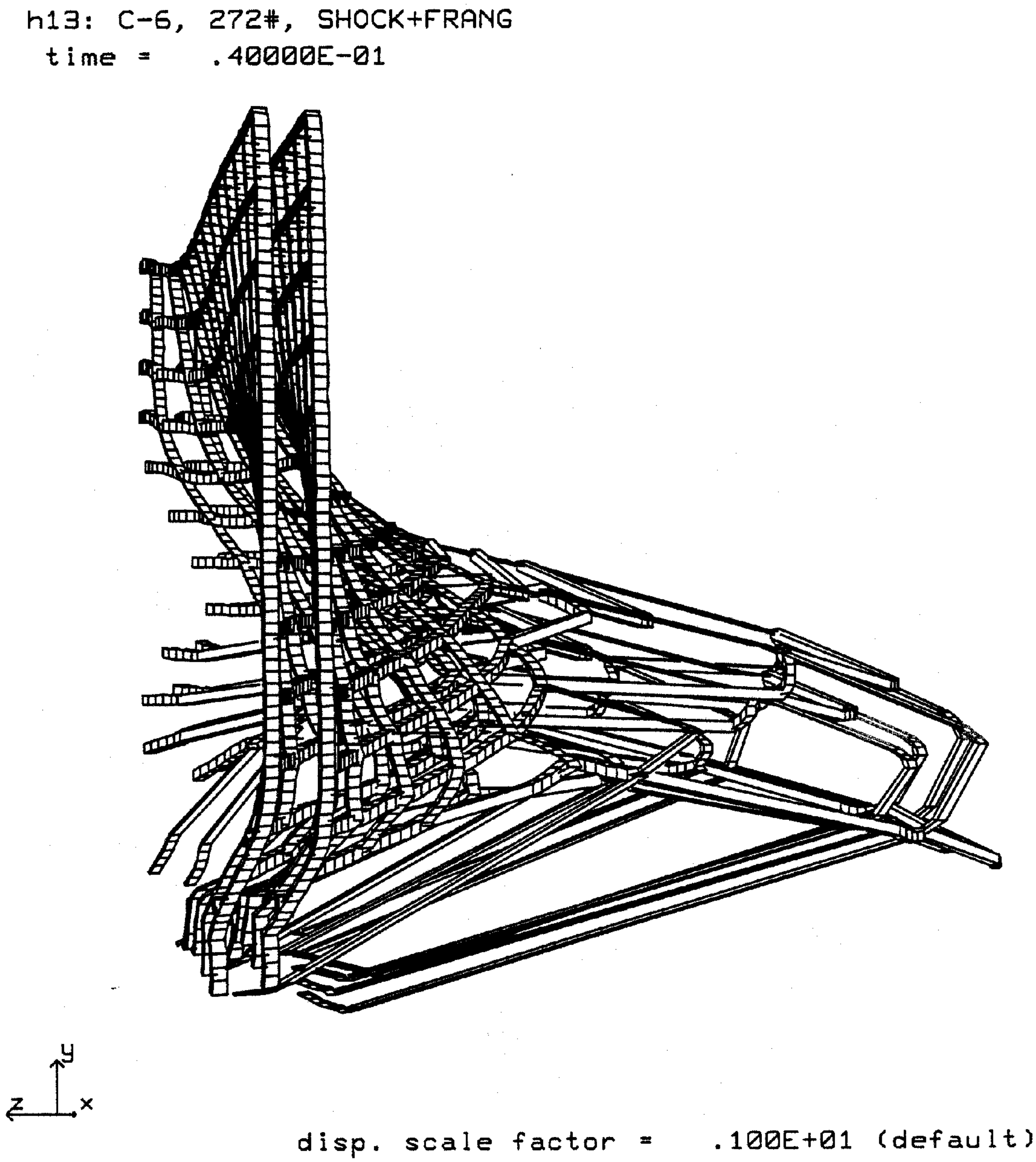

Figure 7 - Deformation of steel reinforcing bars at approximately 0.040 second after loading.

FIGURE 8 - PREDICTED STRAIN IN REINFORCING BARS OPPOSITE CHARGE LOCATION.

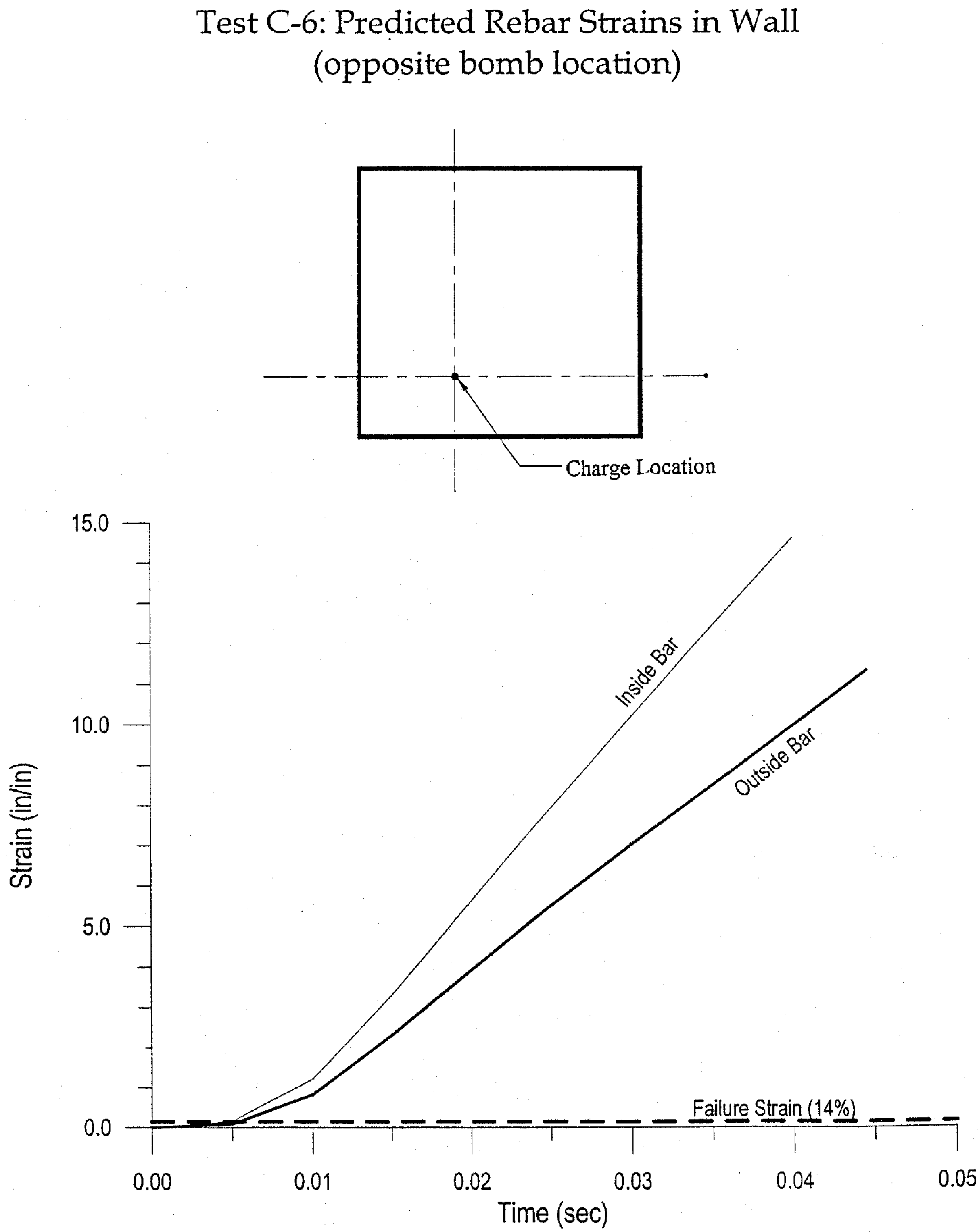

Figure 8 - Predicted strain in reinforcing bars opposite charge location.

FIGURE 9 - PREDICTED WALL FRAGMENT VELOCITIES.

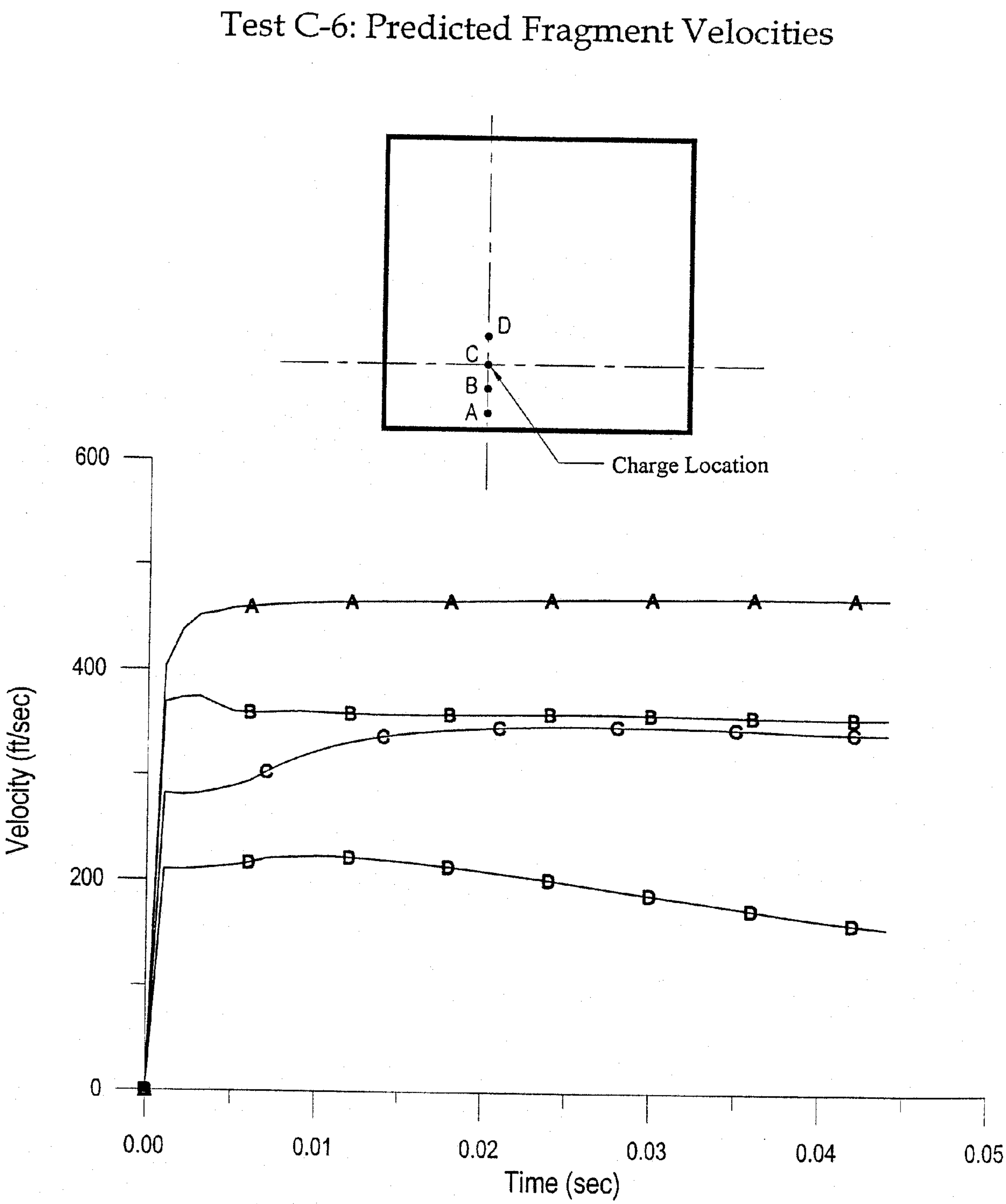

Figure 9 - Predicted wall fragment velocities.

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